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FINAL REPORT

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INVESTIGATION OF ULTRASONIC WELDING OF ALL-BETA TITANIUM ALLOY

J. Byron Jones

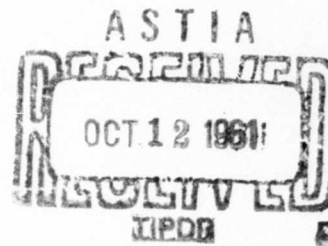
H. L. McKaig

John G. Thomas

September 1961

Prepared under Bureau of Naval Weapons
Contract No. N0w 60-0643 (FBM)

Prepared for
Director, Special Projects Office
Bureau of Naval Weapons
Department of the Navy
Washington 25, D. C.



AEROPROJECTS INCORPORATED
WEST CHESTER, PENNSYLVANIA

CATALOGED BY ASTIA
AS AD NO.

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A E R O P R O J E C T S I N C O R P O R A T E D
West Chester, Pennsylvania

FOREWORD

Investigation of the ultrasonic weldability of a high-strength, titanium alloy (13V-11Cr-3Al) by ultrasonic spot-type welding techniques is reported herein. These studies were made by Aeroprojects Incorporated, West Chester, Pennsylvania, under Navy Contract No. N0W 60-0643(FBM). Liaison and technical assistance were provided by Mr. Richard Gott, Special Projects Office, Bureau of Naval Weapons. The Contract was administered through the Bureau of Naval Weapons Representative, Morton, Pennsylvania, and through INSMAT, Reading, Pennsylvania.

ABSTRACT

The results of this work indicate the feasibility of using ultrasonic spot-type welding to fabricate structural members from thin strips of conditioned all-beta titanium alloy. The strength:weight ratio of the all-beta alloy used for these welding studies had been increased to approximately 1.4 million by heat treatment alone and to slightly more than 1.5 million by cold-rolling the heat-treated material. Furthermore, the ultimate strength:weight ratio of the conditioned all-beta alloy is superior to that obtainable with strips of stainless steel, or special alloys, in similar thicknesses.

Successful multi-ply structures were assembled by both through-welding and ply-by-ply ultrasonic welding techniques.

The welding characteristics of hardened, tool-steel welding tips were found to be superior to those of Inconel X.

Satisfactory levels for input power, clamping force, and welding interval were established by statistical methods in order to secure ultrasonic welds of high strength.

From the information obtained in the present work, structural assemblies of high strength, but lighter in weight than the ones currently in use, can be fabricated from thin strips of conditioned, all-beta titanium alloy by ultrasonic spot-type welding.

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I. INTRODUCTION

Fabrication of structural members from thin strips of metal is feasible if a satisfactory method for joining the strip materials can be developed. Both adhesive bonding and resistance welding have been used for this purpose, but each method has certain limitations. The adhesives currently available can be used without heat at room temperature, but they cannot be used at elevated temperatures because the adhesives currently available deteriorate at elevated temperatures. Resistance welding produces a metallurgical bond, but requires fusion temperatures which cause serious reduction in the mechanical properties of metal. Ultrasonic welding produces a good metallurgical bond at temperatures only one-third to one-half the absolute melting temperatures of the weldment materials (2)*.

A. Summary of Earlier Work

Under a previous contract the feasibility of fabricating structural members from strip material by means of ultrasonic welding was studied (3). Results show improvement in structural efficiency and increases in strength:weight ratio of the welded material.

The ultrasonic joining process substantially reduced the parent material degradation normally associated with resistance welding, thereby increasing the usable material strength, which varies with different materials and different alloys of the same material. For example, in welding across 100% of the width of an AM-355 stainless steel specimen, a change from resistance welding to ultrasonic welding resulted in an increase in usable material strength from 235,000 psi to 270,000 psi. For PH 15-7 Mo stainless steel under the same conditions, a 25% increase in usable strength is shown. These improvements are illustrated in Fig. 1.

An important result of this earlier investigation appears in the welding of titanium alloys. As shown in Fig. 1B, the percentage material strength for ultrasonically welded all-beta titanium is greater than that for the resistance-welded alloy. Furthermore, at a weld width of 100%, the degradation was only 15% of the parent metal strength, which is about half that produced with resistance welding (Fig. 1 and 2). With an alpha-beta 6Al-4V alloy no degradation whatever could be established (Fig. 2). The strengths of welded specimens, with from 5 to 100% of their width ultrasonically welded, fell well within the test scatter band for unwelded specimens which are used routinely to establish parent material strength.

*Numbers in parentheses refer to list of references at the end of the report.

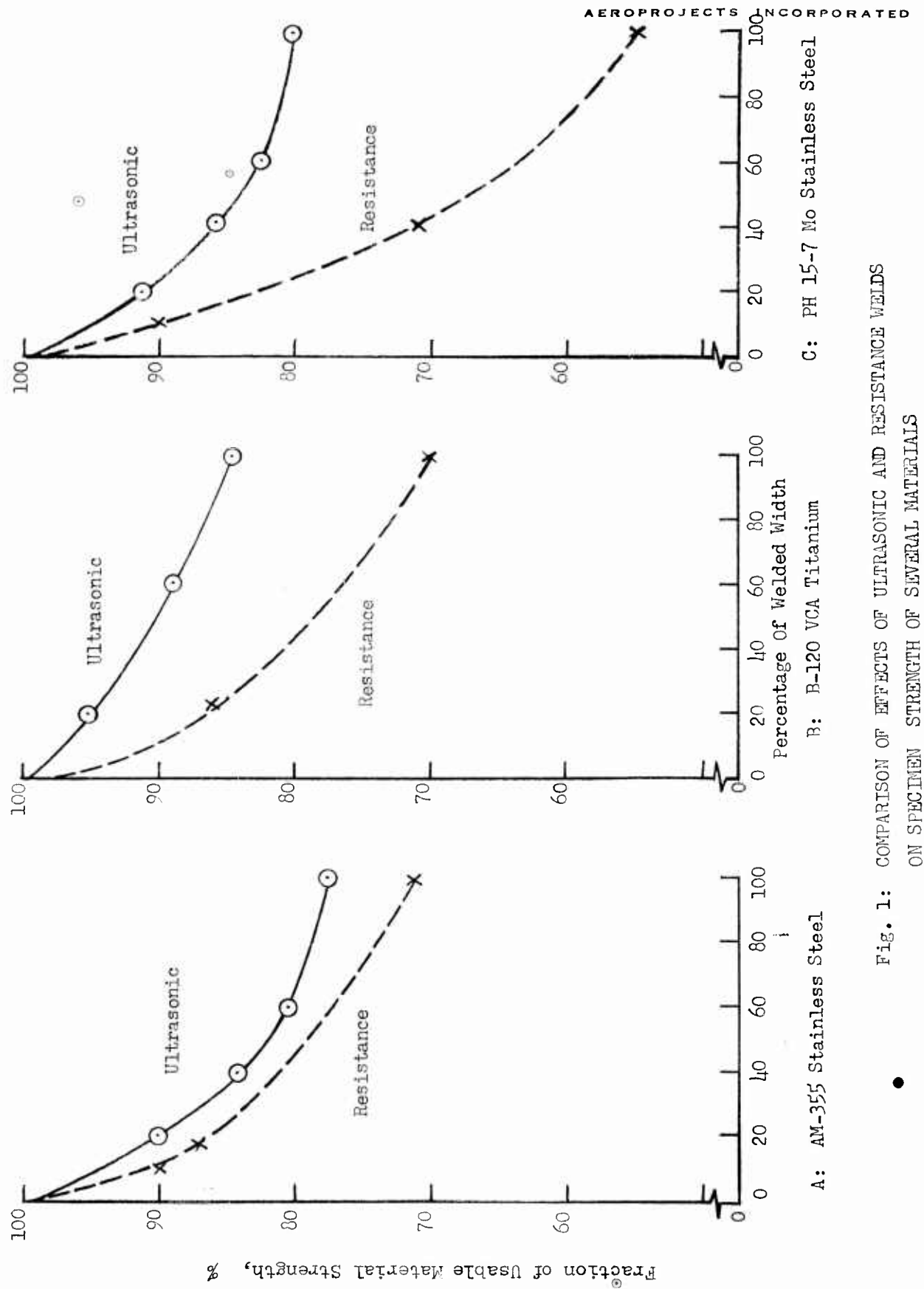


Fig. 1: COMPARISON OF EFFECTS OF ULTRASONIC AND RESISTANCE WELDS
ON SPECIMEN STRENGTH OF SEVERAL MATERIALS

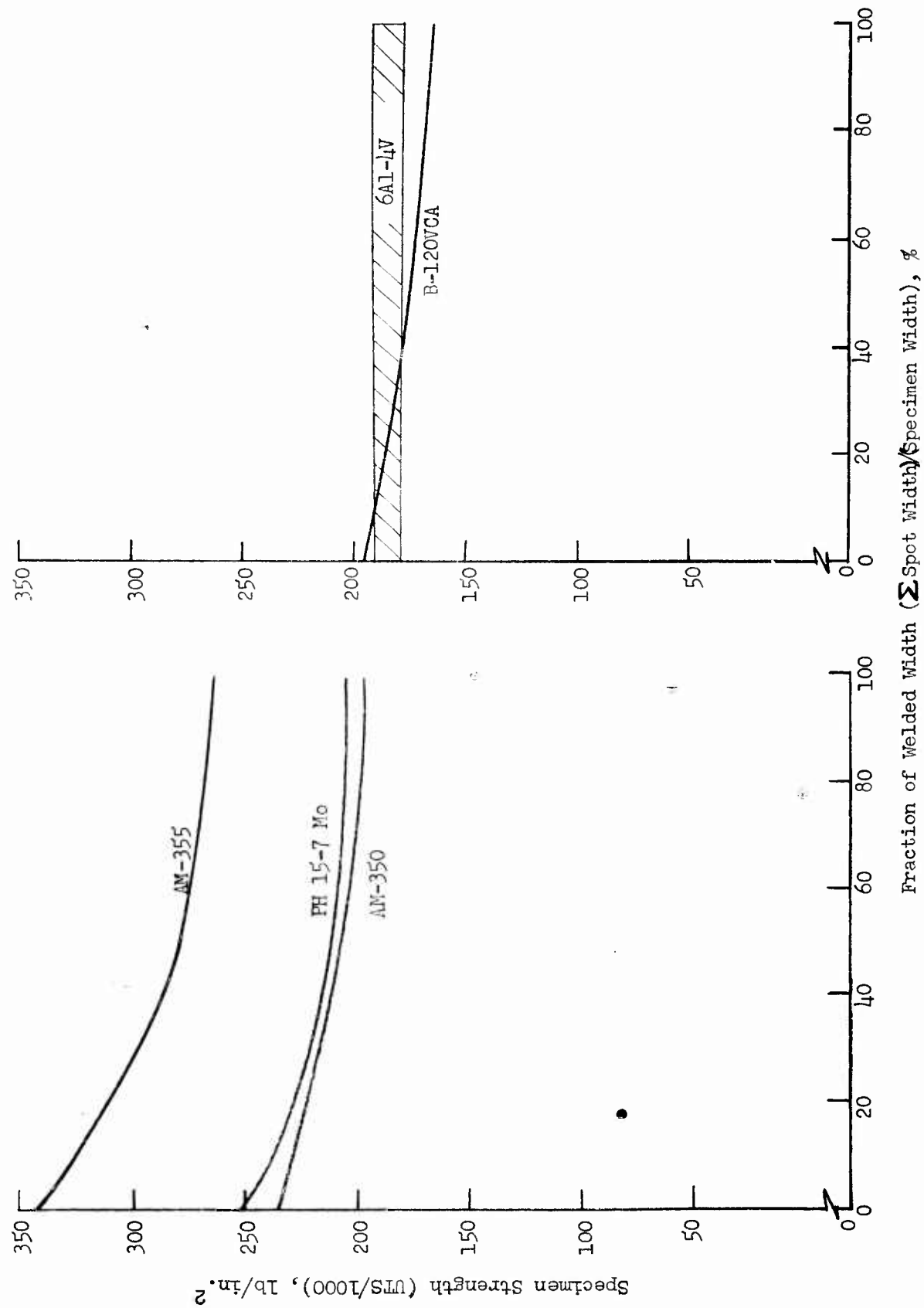


Fig. 2: EFFECT OF ULTRASONIC WELDS ON STRENGTH OF
1/2-INCH SPECIMENS OF SEVERAL MATERIALS

The low degradation, resulting from ultrasonic welding of the titanium alloys, permits a significant increase in strength:weight ratios, as noted in Fig. 3. Other advantages of titanium alloys suggest that with ultrasonic welding, these materials can advantageously replace stainless steels for the fabrication of certain types of structural members.

The titanium alloys used in the ultrasonic welding investigations, prior to this work, did not exhibit the maximum strengths reported for these materials. Results with the 6Al-4V alloy in the heat-treated and aged condition, however, show promise of attaining a strength:weight ratio of 1.1 to 1.2 million. Both this material and the all-beta alloy have a maximum strength of less than 200,000 psi, but the all-beta alloy can be rolled and heat-treated to achieve strengths up to 240,000 psi, which is approximately equivalent to a strength:weight ratio of 1.4 million.

The results achieved to date as well as technological developments in other areas, indicate the advantage of ultrasonic welding and the probable benefits to be derived from continued efforts with it.

B. Properties of All-Beta Titanium Alloy (5)

The all-beta titanium alloy, designated as Ti-13V-11Cr-3Al alloy (Titanium Metals Corporation) and as B-120VCA alloy (Crucible Steel Company), is a beta-stabilized alloy which can be strengthened to high levels by aging and cold rolling. The alloy is useful within the temperature range of -65°F to 600°F. However, after prolonged exposure at temperatures above 500°F, the equilibrium alpha phase occurs, and long-term exposures between 800°F and 1300°F result in beta transformation and eutectoid precipitation.

Because of the alloy additions, 27% by weight, the density of all-beta titanium is 0.175 lb/in.³ compared with 0.163 lb/in.³ for unalloyed titanium. In general, the strength:weight ratio exceeds 1 million for aged all-beta titanium sheet. Subjecting the all-beta alloy to different heat-treatment and/or cold-rolling processes results in a formable material with high strength and good ductility.

C. Objectives

The primary objective of this work has been to establish the characteristics of ultrasonically welded thin strips of high-strength titanium alloys with the view to producing an ultrasonically welded structure. The work here reported embraced five areas specific to this objective:

1. Satisfactory welding machine settings (input power, clamping force, and welding interval) necessary to produce good spot-type welds evaluated on the

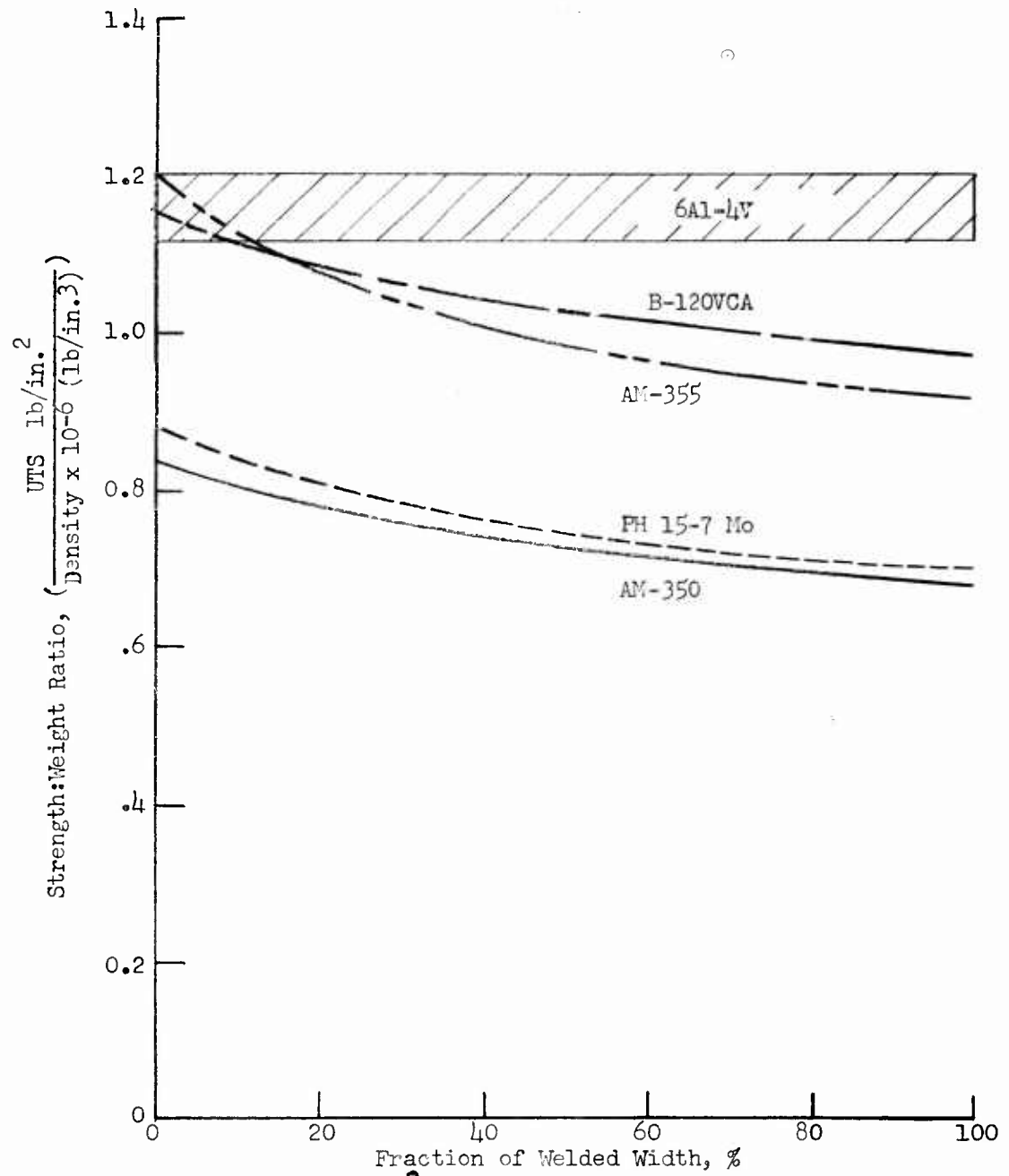


Fig. 3: EFFECT OF ULTRASONIC WELDING ON STRENGTH:WEIGHT RATIOS OF SEVERAL MATERIALS

basis of tensile-shear strength, radiographic inspection, and metallographic examination. The welding characteristics of the beta titanium alloy conditioned to strength:weight ratios approaching 1.4 million were emphasized.

2. Tensile-shear strength variability of two-ply weldments, and room-temperature strength degradation for each material based on statistical methods.

3. Method to effect multi-ply weldments by the ply-by-ply and through-welding techniques for the candidate materials considered the most promising of the two-ply investigation and evaluation of the two techniques on the basis of room-temperature tensile-shear strength and variability of the bonds produced.

4. Influence of sonotrode tip excursion direction in relation to the sheet rolling direction on weld properties as determined by tensile-shear strength measurements of single spot-type welds produced parallel with the tip excursion and transverse to the rolling direction of the strip.

5. The influence of:

- a. Sonotrode tip and anvil material
- b. decreased input-power level
- c. reduced welding time
- d. reduced clamping forces

on weld strength.

II. EXPERIMENTAL MATERIALS, EQUIPMENT, AND EVALUATION TECHNIQUES

A. Materials

1. Titanium

All-beta titanium alloy was obtained from the sources indicated in Table 1.

Table 1

DESCRIPTION OF ALL-BETA TITANIUM TEST MATERIALS

Gage, in.	Condi- tion*	Source
0.004	STACR	Original 0.008-in. STA material, cold-rolled by Hamilton Watch Co.
.008	STA	Titanium Metals Corp.
.010	STCR	Bureau of Naval Weapons, Titanium Welding Program
0.011	STCRA	Aerojet-General Corp., Azusa, Calif.

*According to sequence of treatment- A: aged; CR: cold-rolled; and ST: solution-treated.

2. Tip Material

Inconel X welding tips were used in preliminary welding studies. The results of previous work (3) welding thin-gage stainless steel strips, demonstrated good tip life and welding efficiency for Inconel X sonotrode tips. In welding titanium, however, frequent redressing was necessary to preserve the spherical contour of the 3-in. tip. Therefore, in later tests, Type M-2 high-speed tool steel, heat-treated to a hardness of $R_c 62$, was substituted for Inconel X. Both the sonotrode tip and the flat surface of the anvil were fabricated from the Type M-2 tool steel.

3. Titanium Interleaf Material

A 0.0005-in. unalloyed titanium foil was used as an interleaf between the weldment coupons to reduce the welding energy required. As previously shown (3), with this technique weldments are obtained at lower power levels and reduced welding intervals.

B. Equipment

1. Welding Machine

All welds were produced with a laboratory version of a standard 4-kw ultrasonic welding machine*, shown in Fig. 4; no special alterations or modifications of the equipment were made during the course of this program.

2. Testing Equipment

An Instron testing machine was used to make tensile strength and elongation measurements on ASTM tensile-test specimens (0.5-in. gage). The tensile properties were determined at an extension rate of 0.05 in./in./min.

C. Preparation of Test Specimens

1. Weld-Strength Tests

Simple overlap single-spot coupons, $3/4 \times 3-1/2$ in., were prepared for strength measurements. Before welding, the material was degreased in a commercial metal-cleaning solution (detergent)***, rinsed with water, and air-dried.

2. Material Degradation Tests

For material degradation tests, standard 1/2-in. gage width specimens were prepared with the rolling direction of the strip parallel to the major axis of the coupon.

3. Vibratory-Direction Tests

Weld coupons are sheared from strip so that the long dimension of the tab corresponds to the rolling direction of the strip.

* This equipment is representative of the largest, standard-line, commercially available, ultrasonic spot-type welding equipment.

*** Pennsalt A-27.

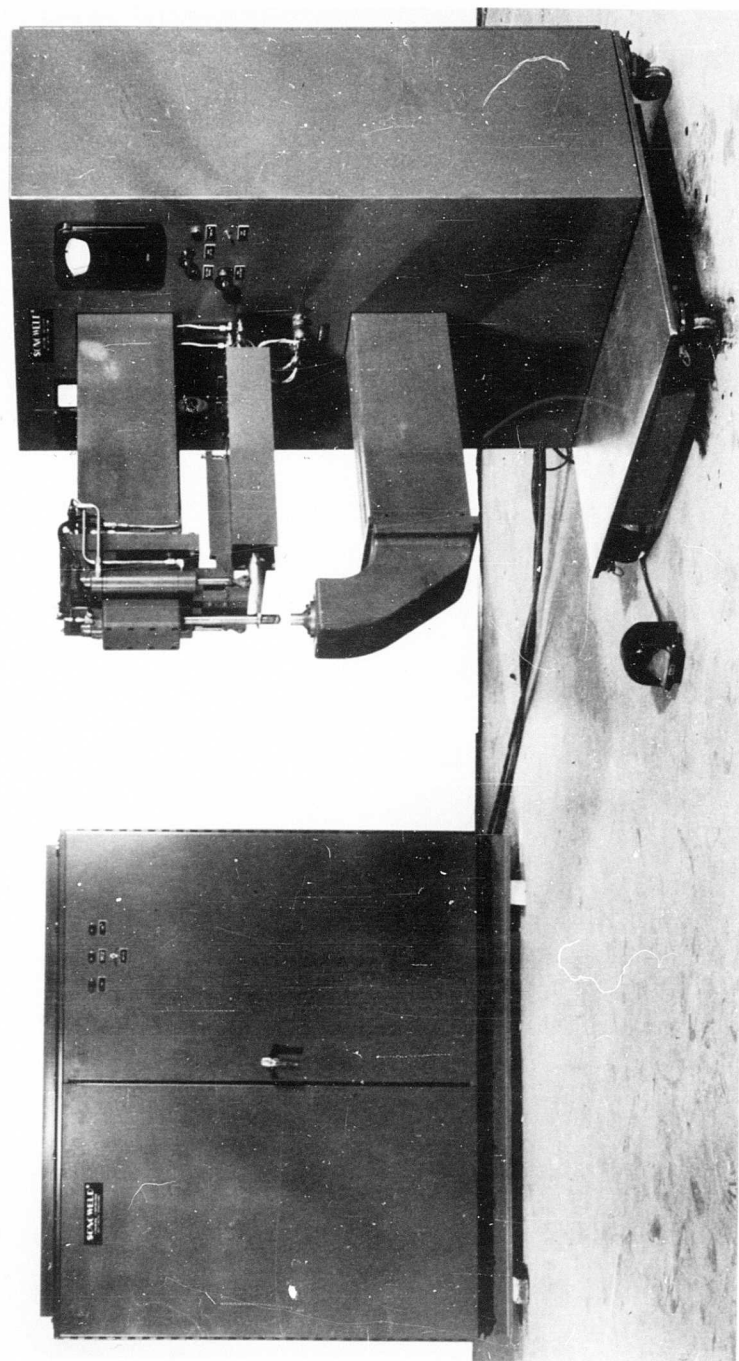


Fig. 4: A TYPICAL 4-KILOWATT ULTRASONIC WELDING MACHINE

In this investigation, however, some tabs were cut parallel to the rolling direction of the strip, and some, transverse. Similarly, some tabs were welded with the vibratory excursion of the welder parallel to the rolling direction of the strip, and some were welded with the vibratory excursion of the welder transverse to the rolling direction of the strip.

D. Evaluation Techniques

1. Statistical Methods

During the course of this work, experiments were designed by G. E. Box's evolutionary operations technique and fractional factorial methods. In some cases, only standard analysis of variance methods were used to evaluate the data.

2. Material Degradation Tests (4)

The material degradation was determined in the following manner.

A 3/4 x 3/4-in. coupon was welded to the center of a standard ASTM 1/2-in. tensile specimen with a single spot and multiple overlapping spots occupying varying portions of the gage width of the specimen. The ultimate strength of each specimen was then plotted against the percentage of specimen width occupied by the welds.

Specimens of each material were welded at machine settings that had been statistically established as producing weld strength. Specimens with weld coverage ranging from 0 to 100% were evaluated to establish the degradation associated with the specific welding machine settings which produced maximum tensile-shear strength.

3. Welding Machine Settings

Scouting studies established approximate welding machine settings (power, clamping force, and welding interval) for producing high-strength weldments. This work consisted of joining single-spot lap-shear specimens at constant energy and varied clamping forces. The resulting welds were shear tested, and the data were used to develop threshold curves (1). Repetition of this procedure at two additional energy levels allowed the selection of the settings of clamping force and energy input (power and welding-pulse time) which produced maximum weld strength. With these settings as a center point, a Box-type experiment was designed and carried out, and the machine settings were further refined so that maximum average weld strength and a satisfactory weld structure were obtained. With the machine settings indicated by the Box experiment, welds were then made and evaluated to determine the mean weld strength and strength variability.

The machine settings included were: power levels of 2400-3000 watts, clamping forces of 300 to 800 lb, and welding intervals of 0.4 to 1.0 sec. In one or two cases, duplicate specimens were welded with and without a 0.005-in. titanium foil insert between the coupons.

III. SUMMARY OF EXPERIMENTAL WORK

Selection of a high-strength titanium alloy with the potential ultimate strength:weight ratio approaching 1.4 million was based on a survey of the physical properties reported for various titanium alloys. Since the all-beta titanium, after appropriate processing, was the only alloy which showed promise of achieving the desired strength:weight ratio, it was selected for further study.

A. Physical Properties of Parent Material

The maximum strength for the all-beta alloy in several gages and conditions was established; tensile-strength and elongation tests were made at room temperature. Standard ASTM tensile specimens with a 0.5-in. gage width were loaded at a rate of 0.05 in./in./min on an Instron testing machine. These results are summarized in Table 2.

Table 2

MAXIMUM STRENGTH OF THE ALL-BETA TITANIUM ALLOY (At room temperature)

Gage, in.	Alloy Condition*	Longitudinal Ultimate Tensile Strength**, psi	Elongation in 2 in.**, %	Strength: Weight Ratio
0.004	STACR	267,250 \pm 3,400	>1	1.52
.008	STA	240,750 \pm 4,200	4.9 \pm 0.6	1.38
.010	STCR	199,300 \pm 250	3.0 \pm 0.5	1.10
0.011	STCRA	239,400 \pm 2,800	2.3 \pm 0.4	1.36

* According to sequence of treatment- A: aged; CR: cold-rolled; and ST: solution-treated.

**90% Confidence Interval.

Reducing the 0.008-in. material to 0.004-in. by cold-rolling resulted in a 27,000-psi increase in tensile strength and in a corresponding ultimate strength:weight ratio of 1.5 million. The ratio for the 0.004-in. STACR material, therefore, is greater than the 1.4-million level specified.

The ultimate strength of the 0.011-in. STCRA material also closely approximates the 1.4-million ratio originally specified. While the strength:weight ratio of the 0.010-in. STCR strip is only 1.1 million, post-weld aging is expected to increase the strength to 230,000 psi or higher.

B. Welding-Machine Settings

The approximate machine settings for welding 0.008-in. STA and 0.004-in. STACR titanium alloy were ascertained by brief scouting studies. The resulting welds were shear-tested, and these data were used to develop threshold curves similar to the one shown in Fig. 5.

During this work, however, it became apparent that a welding interval in excess of 1.5 sec and a power level approaching the power capacity (4000 watts) of the equipment would be required to produce satisfactory weldments with the 0.008-in. material. Welding intervals of this duration resulted in excessive surface deformation, tip sticking, and surface damage. Furthermore, severe surface damage is productive of severe material degradation.

The welding-energy level was reduced by interleaving a 0.0005-in. unalloyed titanium foil between the strip. With this technique, high-strength welds were obtained in 1 sec or less, at an input power of 3000 watts. The 0.004-in. STACR strip was welded, with and without the interleaf, to show the effect of the foil insert on the weld strength at different energy levels (Fig. 6).

The satisfactory machine settings, based on statistical evaluation of the test data, are presented in Table 3 for each gage and condition of the all-beta titanium strip.

Table 3

WELDING MACHINE SETTINGS
FOR WELDING ALL-BETA TITANIUM ALLOY
(Welding with 0.0005-inch titanium foil interleaf)

Alloy		Machine Settings		
Gage, in.	Condition*	Power, watts	Clamping Force, lb	Welding Interval, sec
0.004	STACR	2000	600	0.4
.008	STA	3000	600	.6
.010	STCR	2700	700	.8
0.011	STCRA	2700	700	0.8

*According to sequence of treatment- A: aged;
CR: cold-rolled; and ST: solution-treated.

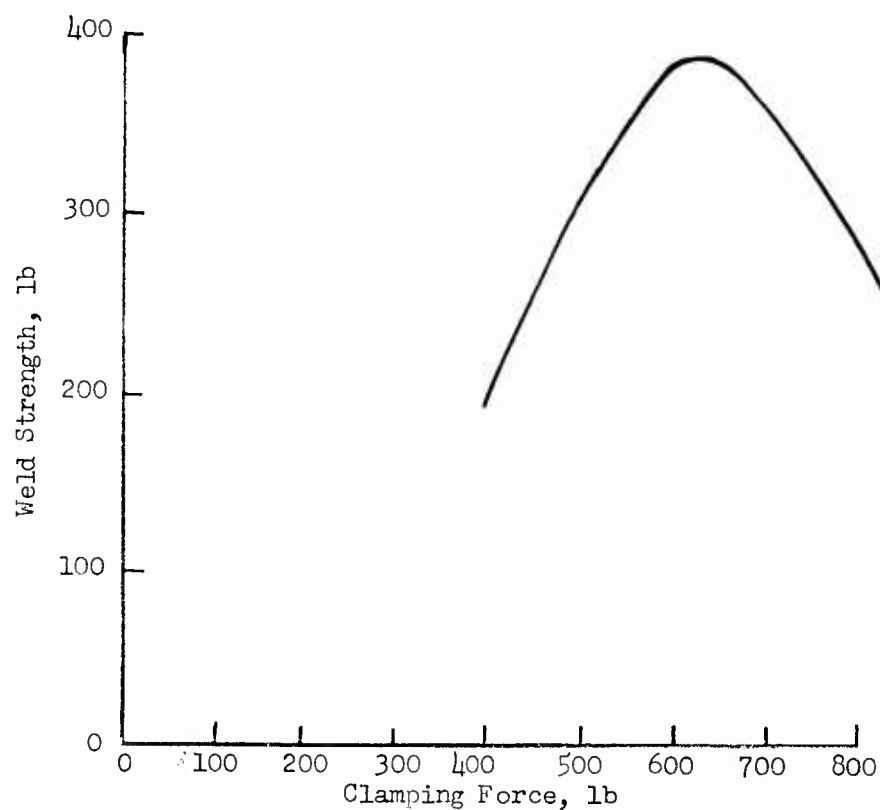


Fig. 5: THRESHOLD CURVE FOR SELECTION OF OPTIMUM CLAMPING FORCE
FOR WELDING 0.008-INCH, SOLUTION-TREATED, AND AGED ALL-BETA
TITANIUM ALLOY WITH 0.005-INCH UNALLOYED TITANIUM INTERLEAF
Constant electrical energy at 3,000 watt-sec

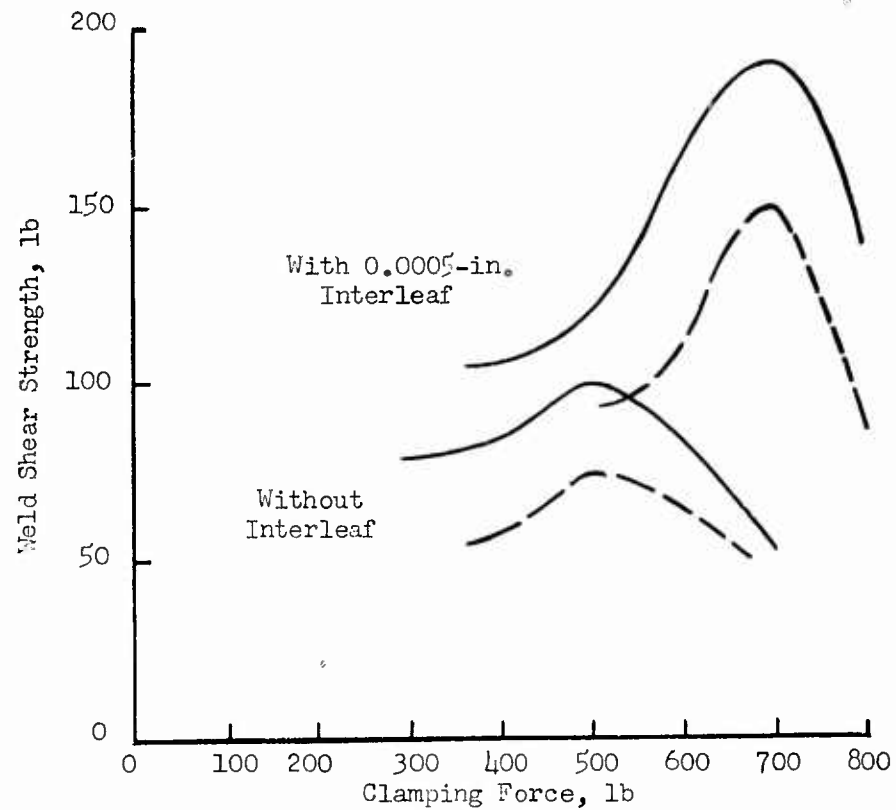


Fig. 6: EFFECT OF TITANIUM FOIL INTERLEAF UPON ULTRASONIC SPOT-TYPE WELD STRENGTH OF SOLUTION-TREATED, AGED, AND COLD-ROLLED 0.004-INCH*ALL-BETA TITANIUM ALLOY WELDED WITH TITANIUM FOIL INTERLEAF

Electrical Energy Input

900 watt-sec

600 watt-sec

C. Weld-Strength and Degradation Studies

The Box experiments yielded the machine settings listed in Table 4 for each of the materials. The mean strength of individual weld spots in each gage and condition of the titanium alloy strip is also presented in Table 4. The relative material degradation, extrapolated to a 100% spot width:specimen width, and the average weld strength, are shown in Table 4 for each material studied.

For reference purposes, the degradation data for each test material are shown graphically in Fig. 7.

Table 4

WELD STRENGTH AND MATERIAL DEGRADATION
DATA FOR ALL-BETA TITANIUM ALLOY
(Optimized machine settings for welding with
0.0005-in. titanium foil interleaf)

Gage, in.	Alloy Condition*	Average Weld Strength**, lb	Average Material Degradation, %***
0.004	STACR	160 + 50	35
.004	STACR (NI)	165 + 45	40
.008	STA	200 + 40	15
.010	STCR	290 + 140	15
.010	STCRWA	270 + 150	35
0.011	STACR	550 + 280	30

* According to sequence of treatment- A: aged;
CR: cold-rolled; NI: welded without interleaf;
ST: solution-treated; and W: welded.

** 90% Confidence Interval.

***100% Spot Width:specimen width.

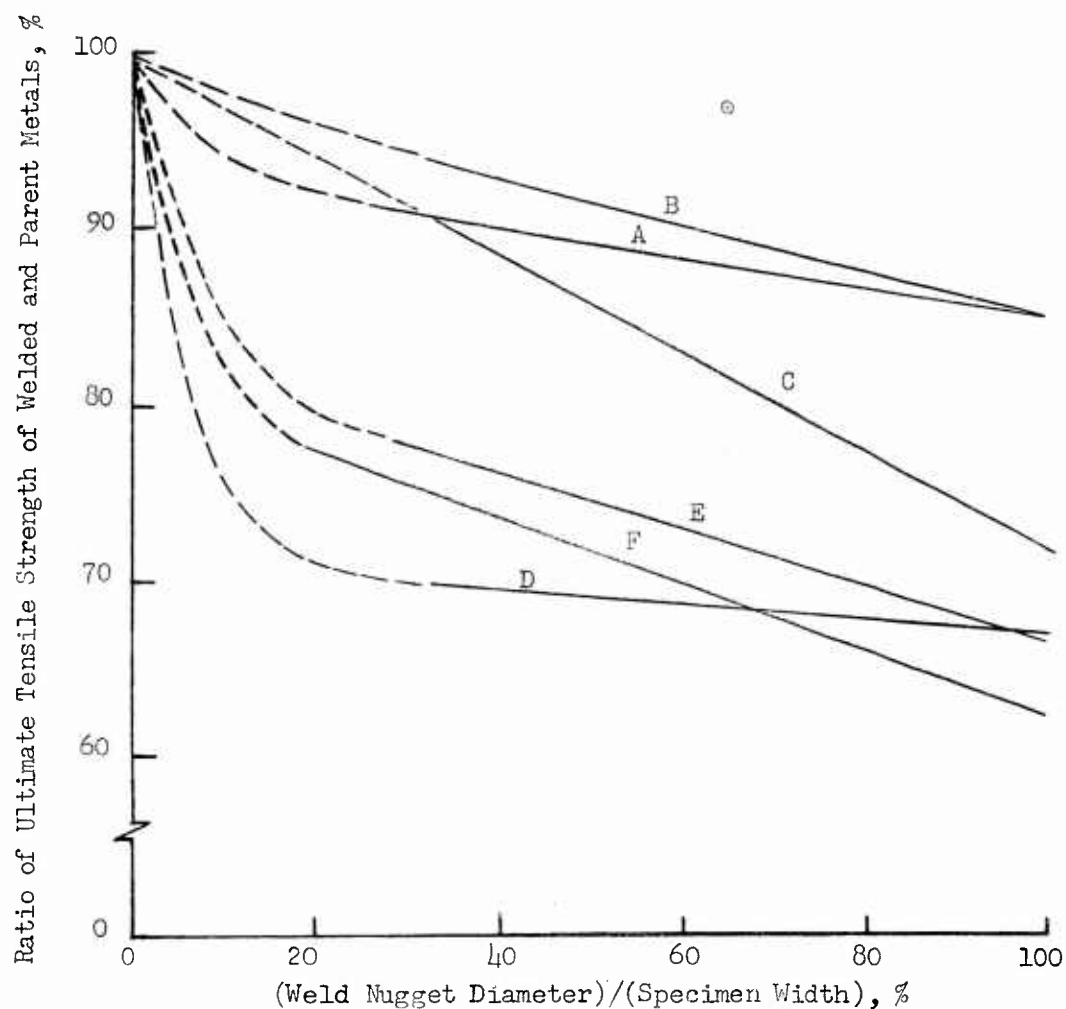


Fig. 7: MATERIAL DEGRADATION CAUSED BY WELDING CONDITIONED*
ALL-BETA TITANIUM ALLOY STRIP

A: 0.008-in. STA	D: 0.004-in. STACR (50%)
B: 0.010-in. STCR	E: 0.010-in. STCRWA
C: 0.011-in. STCRA	F: 0.004-in. STACRWNI

*According to sequence of treatment- A: aged; CR: cold-rolled;
NI: welded without interleaf; ST: solution-treated; and
W: welded.

1. Solution-Treated, Aged, and Cold-Rolled 0.004-Inch Material

Determination of weld-strength consistency was initially conducted with Inconel-X welding tips and anvils. Considerable scatter in these data and variations in the size of the weld spot indicated that the tip contour changed during welding. The work was repeated with Type M-2 high-speed tool-steel tip and anvil surfaces. The weld strength shown in Table 4 is based on the measurement of 39 specimens welded with the latter tips and with a 0.0005-in. unalloyed titanium foil interleaf.

An additional 32 test specimens were welded without the foil interleaf. As shown in Table 4, there was essentially no difference in weld strength and variability obtained by welding with foil interleaf and without. Since tensile shear failure of the coupons occurred by parent metal failure, the welding energy was apparently too great to permit delineation of the foil interleaf effect. The original Box experiment used to determine welding machine settings for this material was conducted with Inconel-X welding tips; the substitution of the M-2 tool steel welding tips apparently increased the welding efficiency sufficiently to over-shadow the benefits derived from the foil-interleaf technique.

2. Solution-Treated and Aged 0.008-Inch Material

Both the Box experiments and the weld reliability data were determined with Inconel X welding tips. The single-spot tensile shear strength and material degradation is presented in Table 4.

The metallographic examination of welded samples selected randomly from the degradation specimens revealed a transformed structure in the weld area (Fig. 8). Diffusion between the foil insert and the titanium sheet was observed in each specimen examined. The material in the weld zone consisted of transformed beta which assumed a block-like structure. A similar structure was observed in previous welding experiments with the all-beta titanium alloy (3). Apparently this type of transformation structure is characteristic of ultrasonic welds in this material when weld temperatures exceed the beta transus temperature.

3. Solution-Treated and Cold-Rolled 0.010-Inch Material

Variability associated with the weld-strength data for the 0.010-in. material was attributed to changes in the contour of the Inconel-X welding tip and this was reduced by substitution of Type M-2 tool steel. The welds were made with a 0.0005-in. unalloyed titanium foil interleaf. Although variability was reduced by this substitution, scatter in the data was unsatisfactory. Additional effort will be required to redetermine welding machine settings and to reduce the spot-strength variability if the 0.010-in. material is candidate for structural assemblies. The degradation results presented in Table 4 indicate that material strength is reduced by approximately 15% at

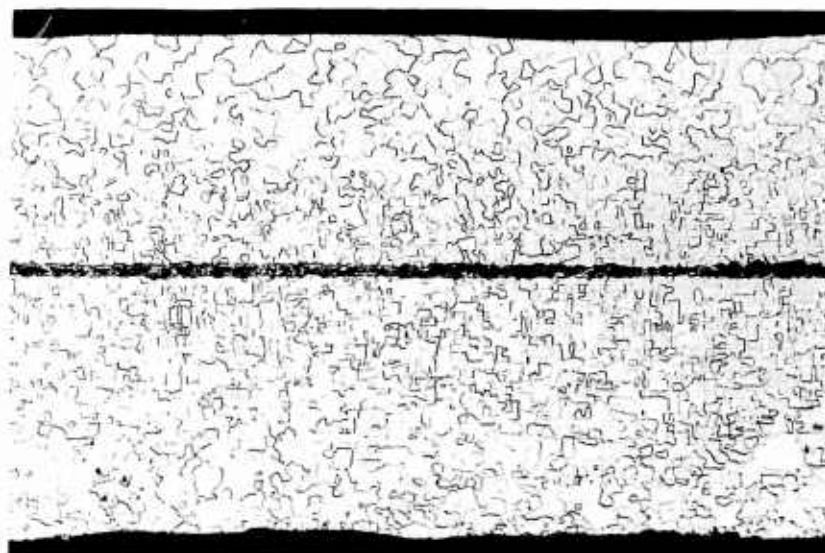


Fig. 8: PHOTOMICROGRAPH OF AN ULTRASONIC WELD IN 0.008-INCH-THICK SOLUTION-TREATED AND AGED ALL-BETA TITANIUM ALLOY
150X



Fig. 9: MICROSTRUCTURE OF ULTRASONIC WELD IN 0.010-INCH ALL-BETA ALLOY WITH A 0.0005-INCH UNALLOYED TITANIUM INTERLEAF (AGED 15 HOURS AFTER WELDING AT 900°F)
150X

Etchant: $\text{HNO}_3 + \text{HF}$

full weld coverage. Microscopic examination of welds in this material also revealed the block-like transformation structure throughout the weld zone. Since the temperatures achieved during welding are apparently as high as those commonly used for solution heat treatment of this alloy, the strength reduction measured in the degradation tests may be ascribed to the elimination of the cold work strengthening of the material.

4. Solution-Treated and Cold-Rolled 0.010-Inch Material Aged After Welding

Sample welds and material degradation specimens were selected from the 0.010-in. STCR material tests and heat treated at 900°F for 15 hr in vacuo. It was expected that this aging treatment would result in an ultimate tensile strength of approximately 230,000 psi. Measurements after the aging cycle indicated that the material failed to respond to the heat treatment. The ultimate strength of the aged material was measured at 198,800 psi as compared with 199,300 psi which was established for this material in the nonaged condition. The exact reason for the failure to respond to the aging treatment was not determined, but slight tarnishing of the specimens was observed after aging. Interstitial contamination may have offset the strengthening which would have been derived in a truly inert atmosphere.

The variability of the material degradation data increased with the postweld aging treatment. The material degradation and the variability of the single-spot strength data were increased for the postweld aged specimens. The nonaged material exhibited strength degradation of 16% at full weld coverage; the postweld aged material indicated approximately 35% degradation at full coverage.

Metallographic examination of the postweld aged specimens revealed an acicular transformation structure within the block-like beta grains. The equilibrium alpha phase occurs as a transformation product when the all-beta alloy is heated within the range of 800 to 1300°F, and the titanium-columbium eutectoid precipitates from solution. The presence of the alpha and the eutectoid precipitate in the beta matrix results in hardening with an accompanying decrease in ductility. Figure 9 shows the matrix transformation in a postweld aged specimen and recrystallization of the pure titanium interleaf.

5. Solution-Treated, Cold-Rolled, and Aged 0.011-Inch Material

The substitution of Type M-2 tool-steel welding tips increased the level of the single-spot weld strength and decreased the strength variation in welds in this material. The mean weld strength of 550 ± 280 lb which was based upon more than 50 measurements, is in excess of that specified by MIL-W-6858A for resistance welds. It is apparent that further refinement of welding machine settings with both the tip and anvil of Type M-2 tool steel or other materials is required.

D. Multi-Ply Welded Assemblies

Multi-ply assemblies were welded with four plies of the 0.004-in. material, without foil interleaf, by through-welding and ply-by-ply welding techniques. Material degradation and weld strength at each ply was determined for the through welds; and weld strength at each ply was determined for the ply-by-ply welded assemblies.

1. Weld Strength

a. Through-Welded Assemblies

Sheets of 0.004-in. STACR all-beta alloy were welded by stacking the four plies in the geometry shown in Fig. 10 and joining all plies simultaneously with a single ultrasonic spot-type weld (machine settings: 3400-watt input power, 600-lb clamping force, and 0.6-sec welding interval). Because of the specimen geometry, each weld in the laminate could be examined and the strength measured. These measurements, together with similar results for single-spot, two-ply welds made at 2000 watts, 600 lb, and 0.4 sec, previously, are given in Fig. 11.

b. Ply-by-Ply Welded Assemblies

The assembly geometry of coupons for ply-by-ply welding tests is shown in Fig. 12. The first two plies were joined with machine settings of 2000 watts, 600 lb, and 0.6 sec. Each additional ply was welded at the same settings in order to determine the influence of the underneath plies on weld strength. The weld spot between the first two plies was placed in the center of the coupon; additional welds were made on each side of the first spot. The results of the individual weld strengths are presented in Fig. 13, together with the standard two-ply strength determined previously. The increase in the weld strength of Weld 1 is attributed to the longer welding interval used in this study (0.6 sec). The sharp decrease in strength of Welds 2 and 3 indicates the effects of the additional subsurface plies. Energy is dissipated into the substrates, and the effective welding energy is reduced. Additional energy is required to raise the strength levels of Welds 2 and 3; the energy dissipation at additional interfaces beneath the two uppermost plies should produce through welding at higher power levels (3).

2. Material Degradation

The degradation encountered in each of the four plies of the through welds is plotted in Fig. 14. The maximum strength loss occurs, as would be expected, at the ply in contact with the powered tip. Indentation and surface scuffing from the powered tip are probably responsible for the higher degradation in the upper ply. The degradation of the substrate plies compares favorably with that established for two-ply welds.

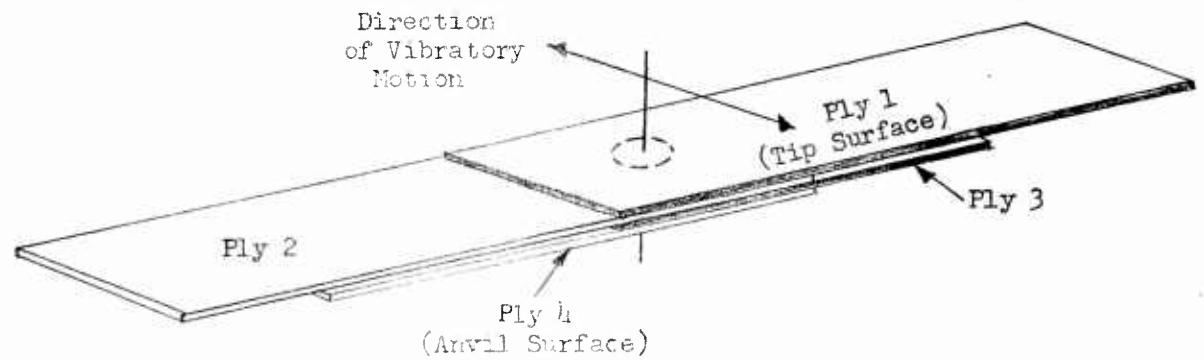


Fig. 10: GEOMETRY OF THROUGH-WELDING ASSEMBLY

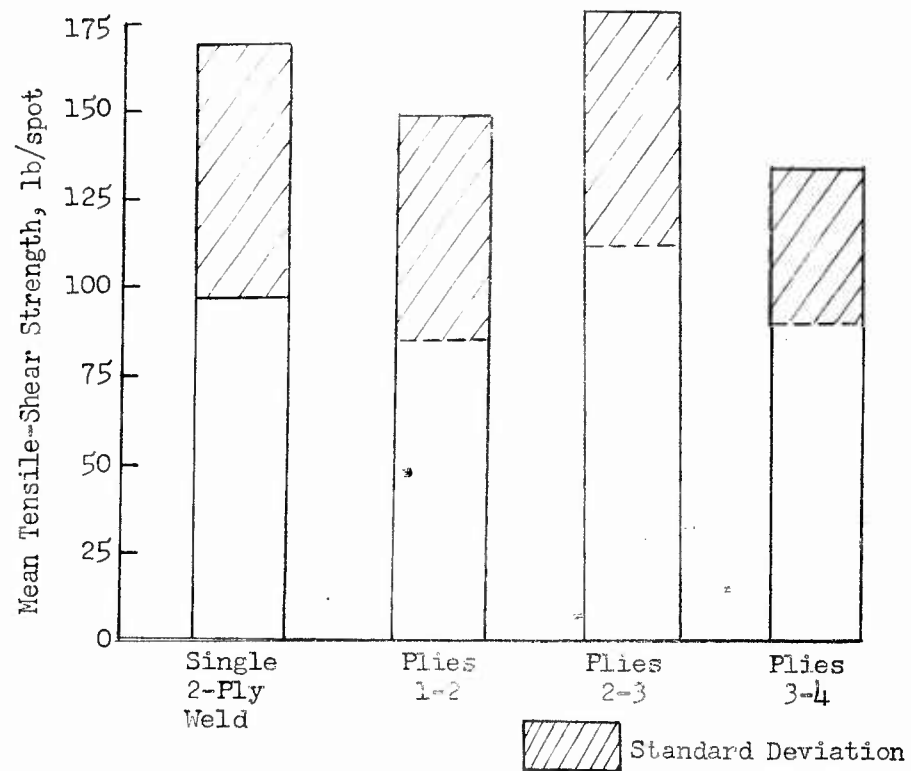


Fig. 11: • ADJACENT-PLY WELD STRENGTH OF THROUGH WELDS IN 0.004-INCH ALL-BETA TITANIUM ALLOY WELDED WITHOUT INTERLEAF

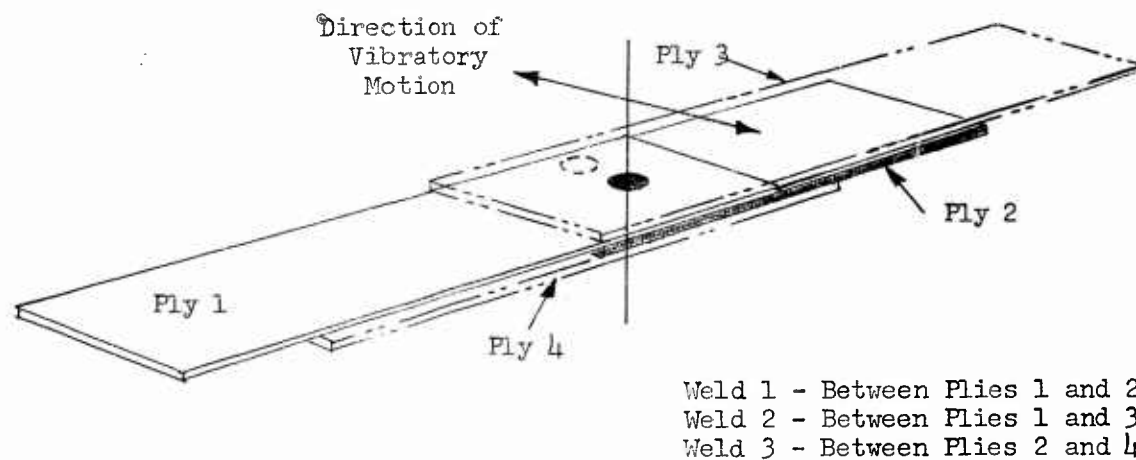


Fig. 12: GEOMETRY OF PLY-BY-PLY ASSEMBLY

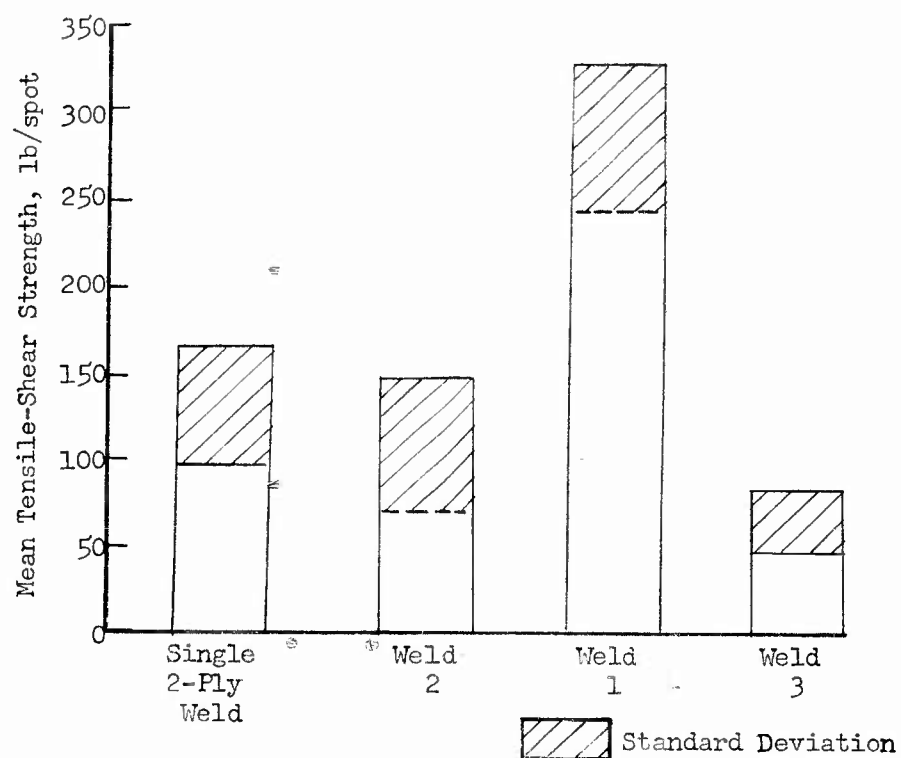


Fig. 13: ADJACENT-PLY WELD STRENGTH OF PLY-BY-PLY WELDING OF ALL-BETA TITANIUM ALLOY WITHOUT INTERLEAF

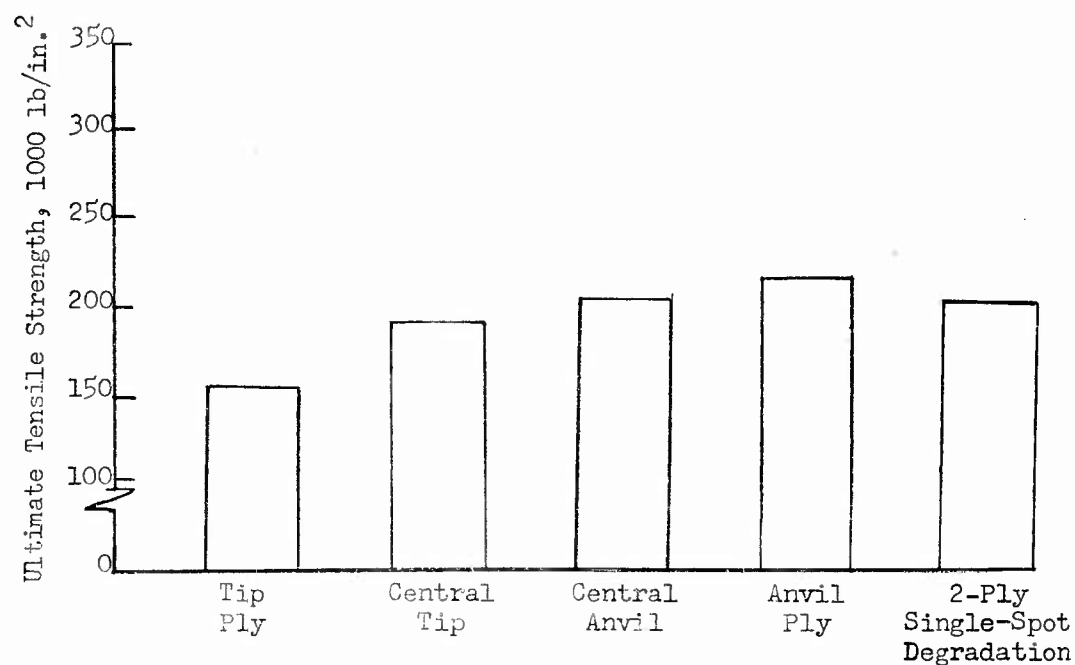


Fig. 14: SINGLE SPOT-TYPE WELD-STRENGTH DEGRADATION OF 0.004-INCH ALL-BETA TITANIUM ALLOY, THROUGH-WELDING WITHOUT INTERLEAF

Table 5

INFLUENCE OF WELD ORIENTATION ON STRENGTH

Gage, in.	Condition*	Direction of Weld Vibration Relative to Rolling Direction	Mean Weld Strength**, lb/spot
0.008	STA	Transverse	400 ± 130
		Parallel	420 ± 115
0.010	STCR	Transverse	610 ± 100
		Parallel	580 ± 110
0.011	STCRA	Transverse	550 ± 90
		Parallel	580 ± 170

* According to sequence of treatment- A: aged; CR: cold-rolled; and ST: solution-treated.

** 90% Confidence Interval.

E. Effect of Vibratory Direction on Spot-Weld Strength

During the generation of an ultrasonic weld, the welding tip oscillation is unidirectional in the plane of the sheet surface. Since the material of interest in this program is rolled strip, the influence on weld strength of the orientation of the rolling direction of the sheet with respect to the vibratory direction, was determined.

The results of the orientation study with the 0.008-in. STA, 0.010-in. STCR and 0.011-in. STCRA strip are presented in Table 5.

This investigation was conducted with tool-steel tips; consequently, the mean spot strength was higher for the 0.008-in. STA and the 0.010-in. STCR material than was previously determined for welds made with Inconel-X tips.

F. Investigation of Ultrasonic Weld Characteristics

1. Sonotrode Tip

Since previous work (3) had shown Inconel X to be a satisfactory tip material for the welding of ultrahigh-strength stainless steel strip, it was originally assumed that tips of this material would be satisfactory for ultrasonically welding high-strength titanium strip.

Accordingly, the work here reported was with Inconel X tips at the outset, and welds of satisfactory strengths were obtained in 0.008-in. STA material. It was found, however, that frequent tip dressing was necessary to obtain welds of uniform spot diameter. Changes in spot diameter introduced unsatisfactory variability in the spot-strength measurements, so an effort was made to improve the weld reproducibility by installing a Type M-2 high-speed tool-steel sonotrode tip and anvil face on the welding machine. With the tool-steel tip, measurements were repeated on the 0.008-in. STA strip at the machine settings previously indicated. Under these conditions, the weld strength increased from 200 ± 40 (Table 3) to 510 ± 70 lb.

In addition to an improvement in weld strength, the frequency with which the tips required redressing was substantially reduced. The life of the tool-steel tips is somewhat shorter than the life of Inconel X tips, probably due to the deterioration of the physical properties of tool steel at elevated temperatures. Since the tip-weldment interface is heated during each welding interval, the tool-steel tips tend to develop cracks upon repeated use. Due to the improved properties of Inconel X at elevated temperatures, tip cracking is delayed.*

* Subsequent to the research conducted on this program, ultrasonic welding tips of Astroloy, General Electric Company high nickel alloy, were found to be quite effective in welding hard, high-strength materials. Astroloy tips require less redressing and retain their excellent physical properties at elevated temperatures for unusually long periods of tip usage.

2. Weld-Spot Strength

a. Clamping-Force Relationship

From past work (1, 2) clamping force is known to be an influential factor in establishing the coupling between the sonotrode tip and the face of the weldment. Energy is delivered to the weld zone with maximum efficiency at a specific value of clamping force which must be determined for each material and welding tip. Clamping forces above or below this optimum condition result in inefficient energy delivery and a resulting drop in weld strength.

The Box experiments were designed to afford easy statistical analysis of strength data and to establish the welder settings which could be expected to produce optimum spot strength consistent with a minimum standard deviation. The variations in single spot-type weld strength associated with changes in the welder settings were examined.

Weld strength was measured at clamping forces below the established optimum level--higher clamping forces produce excessive surface deformation and increase parent-material strength degradation. The improvement of mean weld strength (from 400 lb to approximately 510 lb) as the clamping force is increased from 400 to 600 lb is shown in Fig. 15. These data were obtained from the 0.008-in. solution treated and aged strip; welding was accomplished in this case with Type M-2 high speed tool steel tip and anvil surface.

b. Welding Interval Relationship

The duration of an ultrasonic welding pulse, at constant power, establishes the total energy available to the weldment. Over the relatively narrow ranges of welding interval investigated during this program, an essentially linear relationship was obtained between weld strength and welding interval.

With 3000-watt power input to the transducers and a clamping force of 600 lb, the mean weld strength varied from 415 lb at a welding interval of 0.2 sec to 510 lb at 0.6 sec (Fig. 16).

c. Power Relationship

The relationship between weld strength and electrical power input, within the range of 2000 to 3000 watts, to the transducers is shown in Fig. 17. Input energy, derived from the product of input power and welding time (watt-seconds or joules), determines weld strength in the manner shown in Fig. 18. The data were obtained at 600-lb clamping force. Variation in clamping force with a constant energy input yields the second curve of Fig. 18. These results are consistent with information derived during previous welding investigations (1) and illustrate the broad control of weld quality which can be achieved by the interaction of the three operational variables.

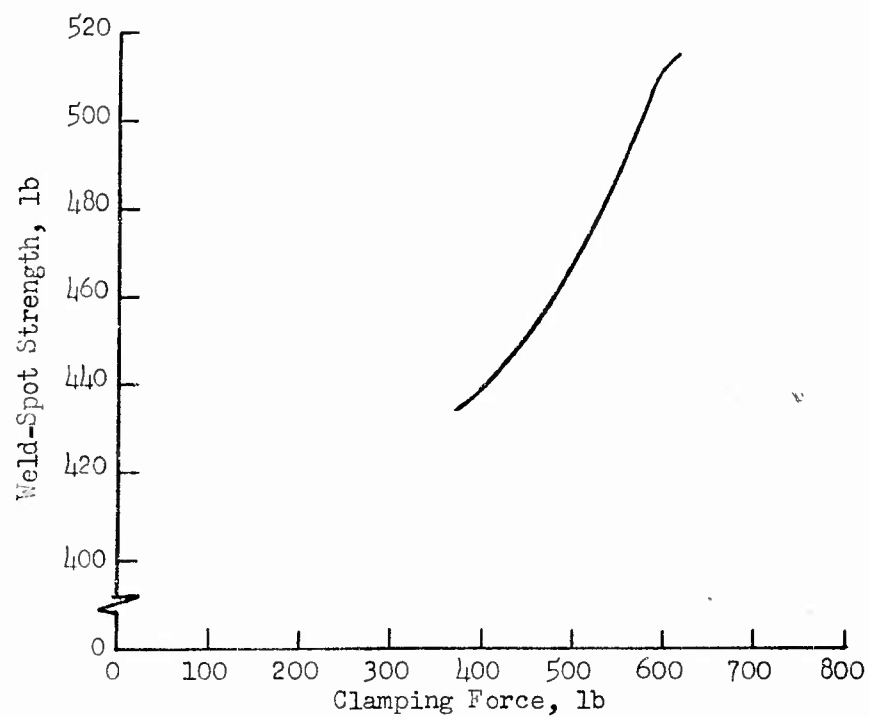


Fig. 15: EFFECT OF CLAMPING FORCE ON
TENSILE-SHEAR STRENGTH
Power: 300 watt
Welding Pulse Time: 0.6 sec

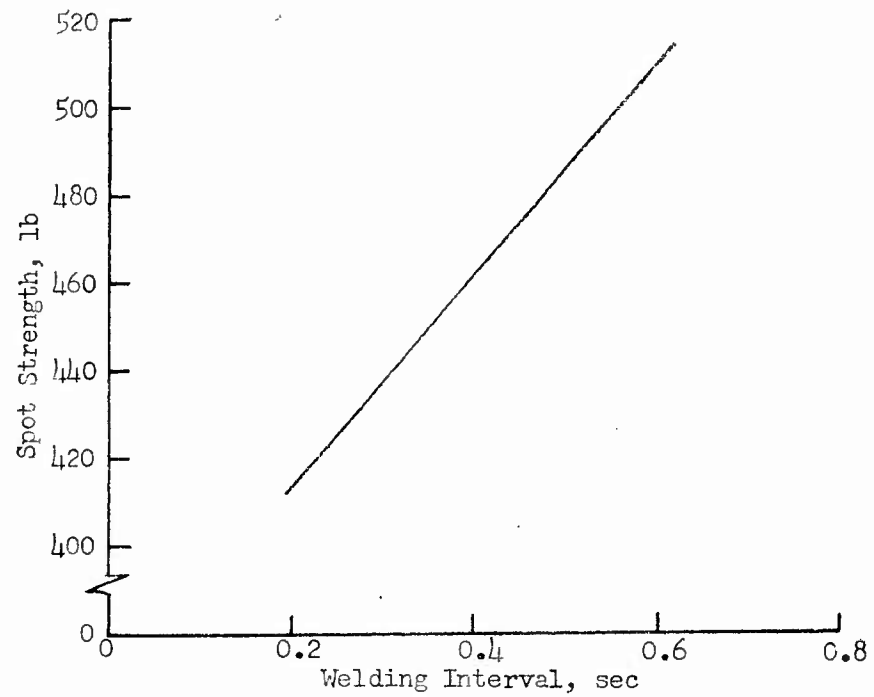


Fig. 16: EFFECT OF WELDING INTERVAL ON
SHEAR STRENGTH OF SPOT-TYPE WELD

Clamping Force: 600 lb
Power: 3000 watts

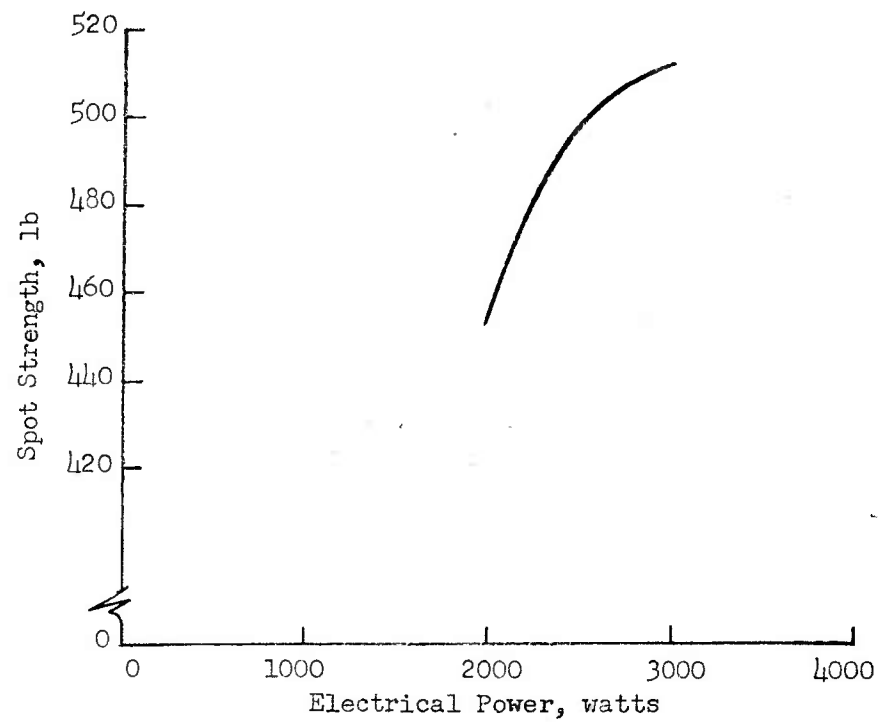


Fig. 17: EFFECT OF INPUT POWER ON SHEAR STRENGTH
OF SPOT-TYPE WELD

Clamping Force: 600 lb
Welding Interval: 0.6 sec

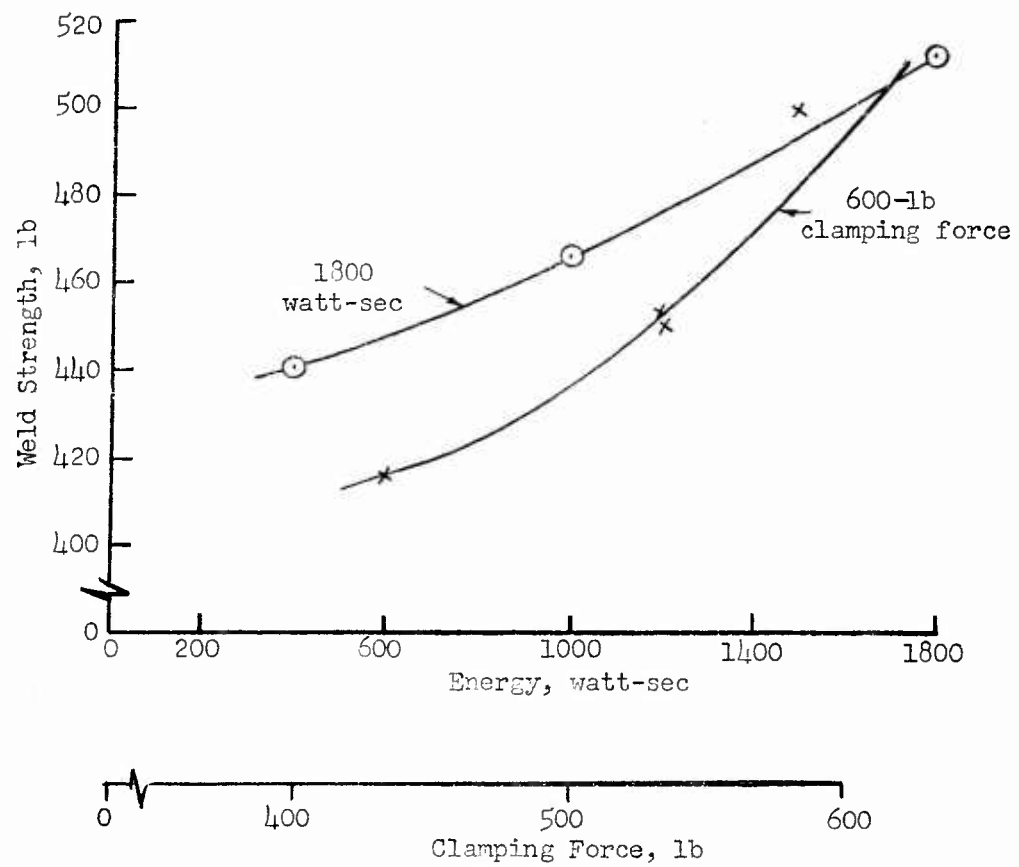


Fig. 18: WELD STRENGTH OF 0.008-INCH SOLUTION-TREATED, AGED STRIP RELATED TO ELECTRICAL ENERGY

IV. CONCLUSIONS

The results of this present research demonstrated the feasibility of ultrasonic spot-type welding of thin gages of conditioned all-beta titanium alloy and fabrication of structural components with high strength: weight ratios.

A. Physical Properties of Conditioned All-Beta Strip

In the course of this work, the ultimate tensile strength of beta-stabilized titanium alloy was improved by heat-treating and/or cold-rolling. The strength:weight ratio of thin strip was increased to approximately 1.3 million by heat treatment (solution-treated and aged) alone. When the STA material is subsequently cold-rolled, the strength:weight ratio increases to slightly more than 1.5 million. Furthermore, the ultimate strength:weight ratio of the conditioned alloy is superior to that obtainable with strips of stainless steel, or super alloy, in similar thicknesses. The strength characteristics and other physical properties of the conditioned all-beta alloys indicate their potential as a material for fabricating assemblies as strong as, but lighter in weight than, those now in common usage.

B. Weld Strength and Material Degradation

The weld strength of the ultrasonically welded all-beta alloy, in all the conditions studied, is equal to or greater than that specified for resistance welds in Specifications MIL-W-6858A.

In general, insertion of an interleaf of 0.0005-in. unalloyed titanium at the weldment interface successfully reduces the energy required to produce a satisfactory bond.

The results of the strength and degradation measurements indicate the sensitivity of this material to the welding conditions employed in fabrication. The more rapid material degradation encountered in the higher strength welds is probably related to the welding temperatures achieved by interfacial heating during the period of ultrasonic exposure. Examination of weld sections indicated that temperatures sufficiently high to exceed the transformation temperature of the alloy occurred during welding, and the resulting retained beta structure in the weld zone developed a characteristic block-like pattern. The degree of heating was sufficient in most

cases to eliminate the cold-work strengthening of the cold-rolled material and to degrade the precipitation-strengthening of the aged material locally in and near the weld zone.

C. Multi-Ply Welding

Successful multi-ply elements were assembled by the through-welding and the ply-by-ply ultrasonic welding techniques. Possibly because of the absorption of energy in the substrates during the ply-by-ply welding assembly, the clamping force and welding energy are difficult to maintain at constant levels as the structure is built up. In through-welding, the material degradation in the ply adjacent to the welding tip is greater than that in the sub-ply because of deformation and scuffing induced by the welder tip.

D. Effect of Vibratory Direction on Spot-Type Weld Strength

The direction of the vibratory motion of the tip, whether applied parallel or transverse to the rolling direction of the thin strip, does not significantly change the strength of the spot-type weld.

E. Influence of Tip Material and Other Variables on Weld Strengths

The substitution of a hardened tool-steel tip for an Inconel X tip resulted in spot welds of much greater strength and in some cases variability was also reduced. The difference in the performance of the tool-steel tip probably results from improved coupling at the weldment face, as well as longer retention of the original tip contour.

The importance of clamping force in the coupling of the sonotrode tip to the weldment face and in the efficient delivery of energy to the weld zone was demonstrated. Threshold curves established and Box-type exploratory experiments confirmed the optimum clamping force for producing good-quality, high-strength welds at a minimum energy level.

F. Summary

The results of the present experimental program establish the benefits to be derived from the fabrication of structures from thin strips of conditioned all-beta titanium alloy by ultrasonic spot-type welding. The ultimate strength:weight ratio for ultrasonically welded all-beta alloy in the heat-treated and/or cold-rolled condition is superior to that of stainless steel or of special alloy strips of similar thickness (Fig. 19).

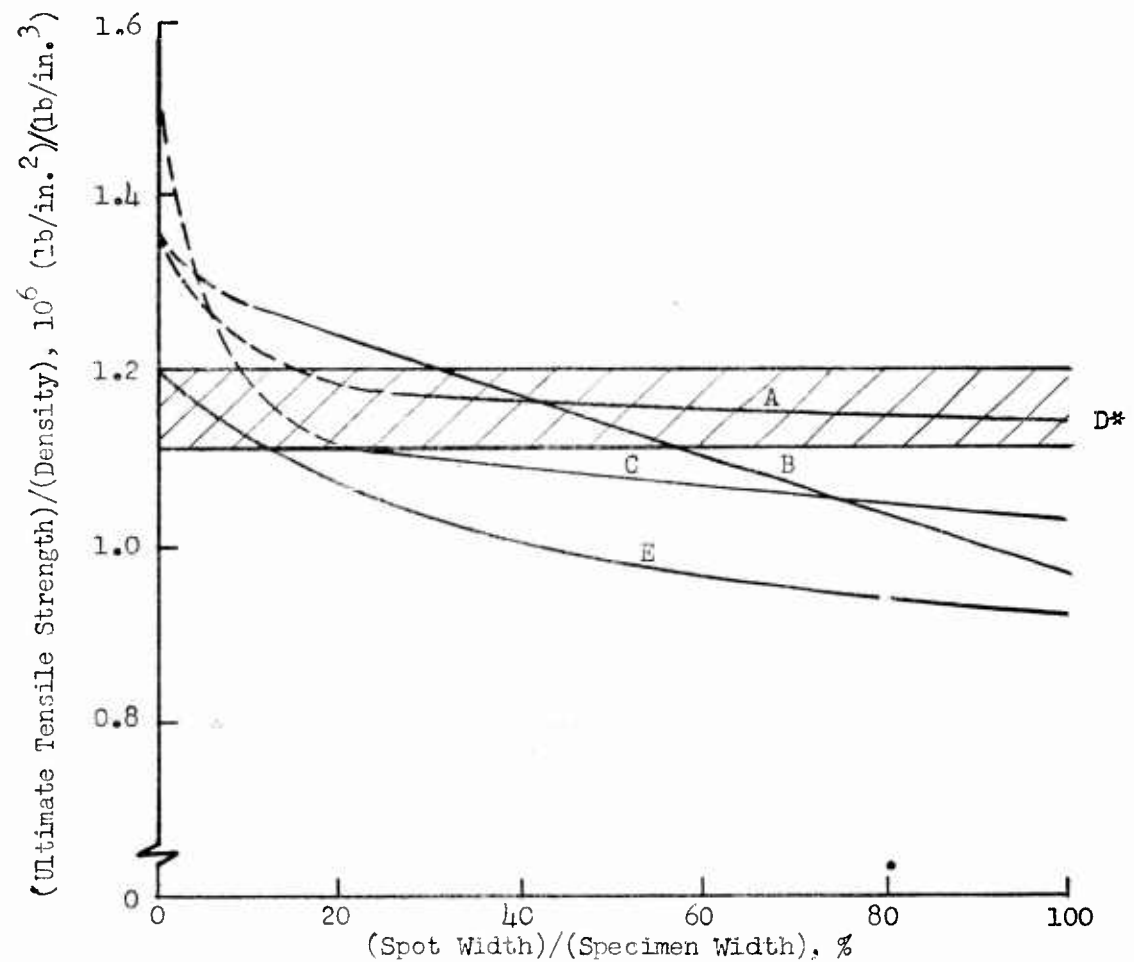


Fig. 19: REDUCTION OF ULTIMATE STRENGTH:WEIGHT RATIO
RESULTING FROM ULTRASONIC SPOT-TYPE WELDS
IN TITANIUM ALLOYS** AND STAINLESS STEEL

Ti-13V-11Cr-3Al

A: 0.008-in. STA

B: 0.011-in. STCRA

C: 0.004-in. STACR

D: 0.008-in. STA Ti-6Al-4V

E: 0.008-in. CR Temper AM-355
Stainless Steel

* Scatter test data with no significant statistical degradation trend.

**According to sequence of treatment- A: aged; CR: cold-rolled; and
ST: solution-treated.

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